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RESEARCH ON EXCITED NITROGEN AND ATMOSPHERIC MINOR CONSTITUENTS USING LIDAR

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A three year program developing and utilizing lidar techniques for atmospheric research is described. This included an investigation of the use of a nitrogen fluorescence lidar as a diagnostic tool during ionospheric RF heating experiments. During 1993 an experiment was performed using our lidar transmitter at the AMOS facility on Mt. Haleakala in Hawaii. Using one of the AMOS telescopes as a receiver data was taken using Rayleigh backscatter and Raman channels as part of the ALOHA '93 campaign. Progress was made toward the development of an intracavity-summed multiple-wavelength Nd:YAG laser for use in a sodium lidar system. Work was initiated to modify the trailer lidar system to include an ozone DIAL capability.

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Contents

1. Program Objectives

The objective of this three-year research program included the use of lidar to measure the density of atmospheric nitrogen which has been excited by electron precipitation in auroras. This study will allow a determination of the spatial/temporal characteristics of the excitation of molecular nitrogen by energetic electrons in an aurora and will define the applicability of lidar as a diagnostic tool in heater experiments such as the HAARP program. The program also included studies of Rayleigh backscatter measured from a mountain top observatory to altitudes of 80 km or higher for study of gravity wave phenomena and studies of minor constituents in the atmosphere, including ozone.

2. Chronological Event Sequence

The first year's work involved experiments relating to the nitrogen fluorescence lidar. In October, 1992, Michael Burka of PhotoMetrics traveled to the HIPAS Observatory near Fairbanks, Alaska. The Mobile Lidar Trailer had recently been moved to HIPAS. The objectives of the trip were to unpack the trailer equipment after the move, to configure the lidar telescope and receiver for use as a photometer at the nitrogen wavelength of interest, 774 nm, to train HIPAS personnel in the use of the photometer, and to prepare the Quantel Nd:YAG laser on the trailer for use in Rayleigh lidar later in the winter.

After correcting minor problems, such as water leaks, the lidar detector was outfitted with a 774.4 nm interference filter and an infrared sensitive photomultiplier. A data acquisition program for photometry was written, and the system tested. Overcast skies prevented collection of useful data, but the photometry system was operational. We trained HIPAS personnel in use of the photometer, and made a training videotape. HIPAS personnel were to be responsible for taking data on a regular basis, and mailing the data to us on floppy disk periodically for analysis.

The Nd:YAG laser exhibited some technical problems. We first converted the power supply to use single phase rather than three phase power; HIPAS does not have three phase. That was successful, but the deionized water pump motor in the laser had failed, preventing any use of the laser. A replacement pump motor was acquired.

While changing flashlamps, it became apparent that a contaminant had gotten inside the oscillator cladding assembly. We suspected that the contaminant was magnesium oxide from outside the cladding that had gotten wet and leaked through a bad seal.

At Hanscom AFB, Richard Garner worked with the Lambda Physik FL2002 dye laser to determine which dyes worked well at the 773.7 nm transition of the First Positive System of nitrogen. We tested several dyes, choosing LDS 765 as the best candidate for use with a Nd:YAG pump laser. A problem with the scanning control mechanism of the laser was found and repaired. It was planned that the dye laser would be shipped to UCLA in January 1993. The plan was to excite nitrogen in Prof. Wong's Ionosphere Simulator plasma chamber as a test of the feasibility of using nitrogen fluorescence lidar as a diagnostic tool during ionospheric RF heating experiments.

At PhotoMetrics, we did some bench tests of the electrical characteristics of a new gated photomultiplier socket. We learned that there was more structure in the rise time curve than had previously been known. This would be factored into the analysis of data to be taken with these sockets. We also carried out some calculations relating to differential absorption lidar for ozone measurement.

The first quarter of 1993 was devoted to nitrogen fluorescence studies at UCLA, auroral photometry at HIPAS and preparations for the AMOS lidar measurement campaign to be held in September 1993. Richard Garner traveled to UCLA to work with Professor Wong and Ralph Wuerker on nitrogen fluorescence experiments. The Phillips Laboratory's FL2002 dye laser, operating in the wavelength range 765-780 nanometers, was used to pump the (A,v=0) state to the (B,v=2) state of molecular nitrogen in UCLA's plasma chambers. Evidence of nitrogen fluorescence in the (2-0) band and the (2-1) band was sought but not found. Using a sub-nanometer resolution spectrometer, we sought a 10 microsecond tail following the exciting laser light pulse ((2-0) band), and an enhancement in the 869.5 nm B-A ((2-1) band) transition. Neither signature was evident, and we do not yet understand what mechanism in the plasma chamber thwarted the fluorescence measurement.

In Alaska at HIPAS UCLA staff gathered several nights of auroral measurements using the PL/GPIM lidar receiver as a photometer. Data was collected at wavelengths of 773.7 nm and at 427.8 nm. Aurora was seen clearly at both wavelengths. Data from

the Poker Flat Meridian Scanning Photometer taken on some of the same nights was forwarded to us. With these data, the trailer receiver was calibrated at the two wavelengths.

The second quarter of 1993 primarily involved preparation for the ALOHA '93 measurement campaign to be held during the summer. Planning was started toward the development of an ozone DIAL lidar for the GPIM mobile lidar trailer.

In late April 1993, Richard Garner attended the NPRSC workshop at UCLA and presented a paper entitled Lidar as a Diagnostic for Ionospheric High Power Radio Frequency Heating Experiments. In this paper he discussed the results of photometry experiments conducted at HIPAS using the GPIM trailer 24" telescope and lidar detector, the results of our nitrogen fluorescence dye laser/plasma chamber experiment at UCLA and his lidar calculations for several different scenarios of lasers and electronic systems to be excited.

In preparation for the ALOHA '93 campaign, the trailer detector and Quantel laser were brought back to Massachusetts. The laser was outfitted with a new oscillator cladding assembly to replace the unit which failed in Alaska. The laser was then able to produce 230 mJ pulses at 532 nm. The detector was substantially modified in order to be optimized for the 1.6 meter telescope at AMOS. The overall length of the detector was reduced and other modifications were made so that the detector would fit within the telescope instrument bay. The Raman dichroic mirror was moved from the lower chamber to the upper and a new housing for the Raman channel was built. The optical train was re-engineered to accommodate the 1.6 meter telescope. Seven cables of one hundred foot length were made to power, control and relay data from the detector. The mechanical shutter was removed. The Rayleigh channel was redesigned to be gated electronically and the Raman channel was designed to be run without any shuttering. The laser, detector and ancillary equipment were shipped to Hawaii for a mid-July test.

The ALOHA '93 campaign was the focus of the third quarter's activity in 1993. In July, Michael Burka, Phan Dao and Vic Baisley traveled to Maui to set up the laser and receiver for the campaign. Our plan was to spend four days setting up the lidar system and three nights taking test data. Our plans were upset, however, by an accident during shipping of the laser system which resulted in damage to the laser by a forklift

and several days delay in the arrival of the equipment on Maui. The laser was installed, but pulse energy was quite low. Mounting the receiver on the 1.6m AMOS telescope required some minor machining, done on site, but was otherwise uneventful.

Three nights of data taking had been planned. The first was scrubbed due to clouds and rain. On the second night we started late because of laser alignment problems and a broken pin in one of the aircraft watch dead man switches. Once on line, we had no success in getting a lidar return signal. Upon the close of our FAA window, we had the operator point the telescope toward a bright star near zenith, then rode a forklift to the instrument coffin and traced the starlight through the detector, confirming that the problem was misalignment of the beam steering optics to the detector. The detector was realigned on the morning of the third planned data-taking session, but that session was scrubbed due to high winds.

During the interim, between the end of the setup trip and the September start of the ALOHA '93 campaign, plans were made for an improved data acquisition system using components borrowed from Phillips Lab/GPOA. The Rayleigh channel was modified to support simultaneous photon counting and analog measurements. A scanning mirror mount was assembled from available components to be used for measuring spatial inhomogeneities in the remnant of the Pinatubo aerosol layer. Also, during this period, Richard Garner wrote a report entitled "Molecular Nitrogen Fluorescence Lidar as a Diagnostic for Ionospheric, High Power Radio Frequency Heating Experiments" for subsequent submittal as a Phillips Laboratory technical report and as a journal article.

In September 1993, Richard Garner and Phan Dao returned to Maui for the ALOHA '93 campaign. A visit from a Continuum laser technician resulted in installation of a new doubling crystal, installation of the amplifier head from the penthouse YG482 laser and realignment of the system, bringing 532nm pulse energy to 260mJ. The improved data acquisition system was installed. The system was tested and succeeded in acquiring data in the Rayleigh channels. No Raman data was collected initially, but this was traced to low PMT voltage and the Raman channel was brought on line two days later. The laser power supply failed early on; it would power the laser oscillator but not the oscillator and amplifier together. The power supply from the penthouse YG482 was shipped to Maui as a replacement. It showed the same erratic behavior, but when used in conjunction with the original YG581 supply the system did function. It was not

determined why the individual power supplies no longer worked reliably with the laser. Once this problem was under control, routine data taking began. Although there were some cloudy nights early in the campaign, good data was collected.

The HAARP Common Data/Interface Format Meeting was held 17 November 1993 at Phillips Laboratory. John Rasmussen facilitated the meeting. Attendees were Pat Bench (PL, HAARP), Lee Snyder (MITRE, HAARP), Mike McCarrick (UCLA, ELF Receiver and Data Format), Keith Groves (PL, HF and VHF Radars), Cliff Brian (Boston College, Scintillation System), Jens Ostergaard (UML, Riometer and Scintillation System), Michael Burka (PhotoMetrics, Lidar) and Leo Collins.

Rasmussen gave a very brief overview of the HAARP site and its data infrastructure. The Gakona site had received EPA approvals. The site is two miles long, with the antenna field at one end and most of the on-site diagnostics at the other. Lidar is about in the middle. Everything is linked by two optical cables, each of which contains 92 optical fibers. The total data rate is 100 Mbit/s. Data sent from an instrument site to the central control area was to be multiplexed, but that multiplexing would be transparent to the user. It was envisioned that all on-site instruments, with the exception of lidar, would be operated remotely from the control area, and that all or nearly all data processing would take place there. Lidar, for safety reasons, requires at least a local technician, but we may still choose to do our data processing in central control. The heater is planned to be operation in 1998, but it is envisioned that the diagnostics will be in place and tested earlier.

The bulk of the meeting dealt with a common data format. The idea is that all heater and diagnostic data should be stored in a central location and in a common data format so that any investigator can access any data stream using a common set of software routines. The format that was suggested by McCarrick of UCLA and also by Poker Flat is called netCDF, which comes from Unidata. It appears that netCDF is compatible with the data stream that will be produced by our present and planned lidar systems. We would modify or rewrite our data acquisition software to output data in the netCDF format, and would write the data to a remote disk which, because of the high data rate, would behave no differently than a local disk. Any number of users can access a given data stream even while it is being written to. NetCDF is platform independent. There is no problem with our using PCs and communicating with UNIX workstations or

whatever platform HAARP settles on for its processors. A large amount of netCDF software is available, including programs to interface with many commercial data processing packages, such as MATLAB and IDL.

There was some discussion of what information the diagnostic instruments need to receive from central. We mentioned that lidar would need antenna trigger information when the antenna was in pulsed mode. The plan is to trigger the antenna from a GPS time signal, and any instrument requiring triggering can use a GPS receiver to trigger from the same signal. Other information such as frequency, elevation, and azimuth would be available through the network.

During the first quarter of 1994, testing and evaluation of a prototype solid state laser capable of producing sodium resonant radiation was completed by Bob Farley. Such a system is desired for high altitude lidar measurements in the polar region. The output energy, spectral and temporal performance were measured as functions of various operating parameters and analyzed for possible improvements in development of a fieldable system. A paper detailing some of the results was written and submitted for clearance. In the course of the analysis, a bug was detected in the laser spectrum analyzer software which resulted in incorrect linewidths being reported. A program to calculate lineshapes directly from the measured fringe patterns was written to correct this error.

The single-cavity sodium laser was used to test two different wavelength calibration systems. One system measured resonant fluorescence from a heated cell containing elemental sodium. The other system used the same sodium cell, but measures rotation of the polarization of a probe beam after the atoms have been optically pumped. In the fluorescent detection system, scattered light background was comparable in intensity to the fluorescence signal. The polarization rotation method should be more immune to scattered background, but we failed to detect any signal in our preliminary experiments.

The Transportable Rayleigh lidar was returned to Alaska from the ALOHA '93 campaign in Hawaii. Some coordination was required to ensure the shipment and safe storage of the equipment at Eielson AFB. HIPAS lacked adequate heated storage.

Processing and analysis of lidar and correlative satellite and balloon data from the ALOHA '93 campaign were continued. Preliminary results indicated wave activity within the range of published values, providing better agreement with rocket data than with sodium lidar measurements. Possible mechanisms for systematic overestimation of wave activity by sodium lidar were debated. Temperature profiles for several nights during the ALOHA '93 campaign were produced, formatted, and submitted to the Upper Atmosphere Research Satellite (UARS) correlative measurement database. These were provided in exchange for access to the corresponding satellite data.

A planning meeting was held to discuss future operation of the mobile lidar trailer. Discussions centered on the modifications needed to the existing detector for future use and on the functional design of a new detector being built in conjunction with the sodium temperature lidar project. The new detector would provide for three data channels. In most cases, these would be one Rayleigh, one Raman and one sodium temperature channel, but in some cases we could choose to use two of the channels for ozone DIAL measurements.

During the second quarter of 1994, a comparison of non-linear optical crystals for generation of sodium-resonant radiation from summed YAG lasers was conducted by Bob Farley. Within experimental errors, the crystals performed as expected. This indicated the low pulse energies obtained with the single-cavity summed YAG laser could be significantly increased by techniques to improve spectral performance or enhance temporal overlap between the 1.06 micron and 1.32 micron emissions. The paper reporting the performance of this laser was submitted to Applied Optics.

Polarization rotation as a method for detecting resonance with the sodium transition was demonstrated. Less than 1 μJ of probe energy and 30 μJ of pump were sufficient to provide readily detectable transmission through crossed polarizers. Both linearly and circularly polarized pump beams produced measurable signals. While intensities of the various hyperfine transitions depended on the specific pump beam polarization, the spectral width of the laser was inadequate to demonstrate such structure, or the sub-Doppler performance anticipated for this technique. The anisotropy induced by the pump is still readily detectable 250 nsec later, as was demonstrated using an optical fiber to delay the probe beam. By enabling signal detection to be gated significantly

after the pump pulse, such a delay greatly reduces noise from scattered pump radiation and electrical interference from the laser firing.

Also during the second quarter of 1994 we computed anticipated lidar returns from plumes produced by rocket launches under conditions of high wind shear for possible tracking and measurement using the mobile lidar facility. Modeling was performed for seasonal and diurnal dependencies, as well as various initial plume morphologies and growth rates. Principal conclusions resulting from these calculations were the importance of selecting regions of low wind shear, and the need to quickly realign the telescope and laser.

During the third quarter of 1994, we began planning modifications to the mobile lidar system to enable it to track a rocket plume in the lower stratosphere and to attempt to measure the molecular and aerosol extinction and backscatter within the plume at 308 nm and 355 nm. These quantities are of interest to modelers of ozone depletion and other aerochemical processes that may take place within the plumes. Our planning activities included software modeling of lidar response to a model plume at four wavelengths, calculation of required and achievable lidar scan ranges and production of a schedule for development and test of scanner, detector and data acquisition systems.

A detailed analysis of theoretical DIAL returns from ozone depletions in rocket plumes using the Phillips Lab mobile lidar facility was conducted. Assumed rocket trajectories, wind profiles, and cloud statistics were used in the study. Possible interferences from Cl_2 and ClO as well as techniques for correcting or mitigating their effects on the measurements were considered. Current scanning capabilities and limitations imposed by the az-el mount, hatch geometry and location were assessed. Seasonal and diurnal variabilities of meteorological conditions for three potential sites and consequent impacts on ozone measurements were compared.

In general, early morning observations during winter would provide the best data, thus favoring a West coast launch site. However, an afternoon launch from the West coast during summer represents the worst possible scenario. As it is desirable to study seasonal dependencies, site selection is necessarily a compromise, and valuable measurements would be possible from any of the three missile ranges considered: Kennedy, White Sands, and Vandenberg.

The efforts in the fourth quarter of 1994 focused on development of a scanning ozone lidar. The PL/GPIM Mobile Lidar Trailer was returned to Hanscom AFB. We unpacked the trailer and repaired minor damage that occurred in transit. Ceramic capacitors were reinstalled in the excimer laser and it was operated with xenon chloride at 308 nm. Although functioning, it was judged to be in need of refurbishment. The tube was removed for refurbishment by Lambda Physik. Unstable resonator optics for 308 nm were procured. First steps were taken toward realigning the Nd:YAG laser and installing its frequency tripler. Relay mirrors for 308 nm were procured. The Nd:YAG beam expander and relay optics were measured at 1.06 μm and found to be unsuitable.

The wavelength characteristics of the scan and kick mirrors, designed for 355 nm and 532 nm, were measured at 1.06 μm and 308 nm. The aluminized scan mirror was acceptable at all wavelengths, but the kick mirror was poor at 308 nm and not useable at 1.06 μm. As with the relay optics, potential solutions were devised.

A conceptual design for adding a second degree of freedom to the scanner was developed. Optics were tested at 308 nm and 1.06μm and found to be acceptable. Mirror curvatures and separation were measured. Detector shutter and synch signal generator were tested. A new optical layout for four channel operation was developed. The necessary lenses, dichroics and interference filters were procured, and physical modification of the detector was begun. Matching interference filters were loaned to Aerospace Corp. for sky background radiance measurements. Several detectors and amplifiers for the 1.06 μm channel were researched, including InGaAs photodiodes and IR-enhanced Si avalanche photodiodes. One of the latter was chosen.

Spreadsheet simulations of the lidar signal/noise under day and night sky conditions were produced. Simulations of the tracking angles and angular velocities required under a variety of launch direction and wind condition scenarios were produced, indicating that the field-of-view accessible to the scanner in the current trailer configuration was inadequate. Three potential solutions were devised. These tracking simulations also set constraints for scanner motor performance.

During the first quarter of 1995 work continued on development and testing of the scanning ozone lidar. The excimer laser was refurbished by Lambda Physik and

reinstalled. The main scanner assembly was designed and machining was initiated. Work on the detector was completed except for installation of the 1.064 μm channel. Measurements of ozone profiles were made at Hanscom AFB and effort was directed toward enhancing signal-to-noise. A meeting with the Aerospace group was held at PL/GPI on March 22 to present the system and discuss future plans.

During the second quarter of 1995 work continued on testing and deployment preparation of the scanning ozone lidar. The beam handling apparatus was completed for the 308 nm and 532 nm channels, including installation of mirrors. Ozone data was collected while operating in the vertical mode. Efforts were concentrated on reducing locally produced electrical noise. A meeting with the Aerospace group was held at PL/GPI on May 26, 1995 to present the system and discuss future plans.

3. Summary

Research leading toward a nitrogen fluorescence lidar as a diagnostic tool for ionospheric RF heating systems was performed. The nitrogen lidar could be used as a heater diagnostic at the HAARP heater facility in Alaska. Measurements using the transportable lidar laser transmitter were made during the ALOHA '93 campaign which yielded middle atmosphere temperature profiles for correlation with other campaign measurements. A prototype intracavity-summed multiple-wavelength Nd:YAG laser for use in a sodium lidar system was demonstrated. Development leading toward a scanning ozone DIAL capability for the transportable lidar was initiated.

4. Publications

The following refereed journal articles were published concerning research performed under this contractual effort.

Garner, R. and P. Dao, Molecular nitrogen fluorescence lidar for remote sensing of the auroral ionosphere, J. Geophys. Res., 100(D7), 14,131-14,140, 1995

Farley, R. and P. Dao, Development of an intracavity-summed multiple-wavelength Nd:YAG laser for a rugged, solid-state sodium lidar system, Appl. Opt. 34, 4269-4273, 1995